Standards for Bio-Based, Biodegradable and Compostable Plastics: Call for Evidence

Consultation response from the Institution of Chemical Engineers (IChemE)

On behalf of the Institution of Chemical Engineers, we would like to respond to the above consultation document.

1. Government has made clear that we want to eliminate all avoidable plastic waste and to move towards a more circular economy. What role, if any, is there for bio-based plastics to play in achieving the outcomes listed in paragraph 1.7? How could the circularity of these materials be reflected or measured? What is the evidence in support of your view?

Plastics are so firmly embedded in the economy that, rather than trying to eliminate them completely, the focus needs to be on managing them systematically. The resource use in producing plastics is small compared to the environmental impacts of plastics lost to the environment. Therefore, the problem in managing plastics is to prevent “leakage” from the economy into the unconfined environment and to reduce the damage caused by plastic waste that does escape[1]. Plastic released into the environment is carried by natural environmental flows and therefore ultimately enters the oceans; this is the reason why plastic pollution is most damaging in the oceans[2,3]. Management of plastics requires a coordinated and innovative approach throughout the value chain to achieve an integrated business model that incorporates efficient resource utilisation, applications, and after-use utilisation, including chemical recycling, mechanical recycling, and energy/thermal recovery[1,4]. Furthermore, a majority of plastic litter comes from unthinking human action. Therefore, it is also imperative to modify the behaviour that leads to human litter, through education or persuasion reinforced by applying penalties for littering[1].

The idea of a totally enclosed waste-free “circular economy” is far too simplistic; it is superficially appealing but is a practical impossibility. The Second Law of Thermodynamics applies universally. In this context, it means that all materials become degraded or contaminated in use so that they eventually reach the point where more resources are needed to recycle them than are required to replace them; i.e. waste is inevitable and therefore waste management, including energy recovery, must be part of the integrated approach to managing plastics[1]. Many “recycling” processes actually turn used materials into lower-grade products. For example, once thermoformed polypropylene food trays have been recycled the material cannot be used as food packaging, but it can be used to produce plastic carrier bags. ‘Downcycling’ is still desirable because it keeps the material in the economy in use for as long as possible, but it cannot avoid the inevitability of materials finally becoming waste. Recycled materials may need to be blended with virgin plastic to produce materials of an acceptable quality. Thus increasing circularity will not suffice to eliminate further plastic pollution completely[1,2]. The scientific fact that all plastics will inevitably become waste, although recycling can delay the process by extending the life of materials in the economy, brings out an important but often overlooked point: eliminating losses of plastics from the economy into the environment must include managing end-of-life plastic waste[1]. One of the hidden dangers in unrealistic “circular economy” or “zero-waste economy” concepts is that they take attention away from the unavoidable problem of dealing with final waste. Energy recovery from waste provides an economically and environmentally attractive way to use waste plastic so that it must be part of any responsible policy for managing plastics.

Sourcing plastics from biological materials does not necessarily support this integrated approach to the use of plastics; therefore, any idea that bio-based plastics are a general solution is ill-founded[1]. It is important to recognise the clear distinction between bio-based and bio-degradable materials: 'bio-based' refers to the feedstock used to make the plastic whereas 'bio-degradable' refers to a property of the material. Bio-based materials are not necessarily bio-degradable. Biological sourcing may even use more resources than production from fossil reserves; cotton bags are a well-studied example – the inputs of water and agrochemicals to cotton production make cotton a much more resource-intensive material than plastics[5].To reduce the environmental impacts of plastics, the key property is biodegradability not whether the material is bio-based. Furthermore, many biobased plastics are less amenable to recycling or other approaches to life extension than common fossil-based plastics. Therefore, the entire life cycles, preferably over many use cycles, must be considered before recommending bio-based or biodegradable plastics.

Specialist properties of some bio-based and/or biodegradable polymers may offer niche markets - for example biocompatibility may be of value in healthcare applications such as disposable wound dressings, while polylactic acid has long been employed for resorbable sutures – but these represent very small volumes. Bio-based polyethylene derived from ethanol from the fermentation process of starch or cellulosic materials shares similar chemical properties to fossil-based polyethylene and these bio-based plastics can be recycled and reused.

There are also other types of bio-based plastics which involve blending bio-based materials such as saw dust and rice husk. The number of times these blended materials can be recycled without deteriorating their properties is much lower than neat polymers and as such can produce products of poor quality. The current plastic recycling infrastructure is not set up to separate these lower quality plastics from higher quality conventional plastics. Without the ability to separate out the lower quality bio-based plastics, the circularity potential of the plastics recycling system can be compromised. If waste facilities can separate out the lower quality bio-based plastics, then bio-based plastics could play a role in the circular economy, albeit a different one to conventional plastics.

On the other hand, the blending of cellulosic material especially those generated from plantations (E.g. a palm oil plantation yields large amounts of biomass wastes in the form of empty fruit bunches (EFB) – a fibrous material of purely biological origin) can actually help to transform biomass into value-added bio-based plastic products. This can bring about better economic prospects to the agricultural industry. Consumers need to be given clear information about this kind of bio-based plastic so that they are aware of its composition as well as the available recycling method.

References

[1] Clift et al. (2019), 'Managing Plastics: Uses, Losses and Disposal'. Law, Environment and Development Journal.

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[4] Kawashima et al. (2019) Macromol. Mater. Eng., 304, 1900383

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2. With regards to their environmental impact, and particularly greenhouse gas emissions, what quantitative evidence is available on the environmental impacts of producing bio-based plastics and managing them at end of life? How does the evidence compare to conventional fossil-based plastics?

It should be stressed that ‘environmental impact’ is not a simple concept. In developing standards and measurement techniques, clarity is essential as to what ‘impacts’ are to be minimised – greenhouse gas emissions; tonnes of carbon; specific pollutants; visual impact of waste; harm to wildlife; etc. Furthermore, the overall impact of using a material or artefact depends not just on initial production and end-of-life management but on how many times it can be used or recycled. Therefore, full life cycle analyses considering specific uses are essential if a standard is to be framed to achieve the desired effect.

Spierling et al. (2018)[1] provides a review of life cycle assessments (LCA) of bio-based plastics. A lack of harmonised standards limited the comparative study to the LCA metric, Global Warming Potential. They concluded that bio-based plastics contributed positively to all three pillars of sustainability and could potentially save 240 – 315 million tons of CO_2eq annually by substituting 65.8% of all conventional plastics. The limitations of the study included the already mentioned critical methodological aspects, missing information for some bio-based plastic types as well as missing information on plastic demand of some fossil-based plastics and question marks behind the validity of a direct comparison of biobased and fossil-based results due to lack of a joint product category rule.

Simon et al. (2016)[2] compared aluminium, polyethylene terephthalate (PET), polylactic acid (PLA), carton and glass beverage bottles. It was found that the consumer bottles generated the least greenhouse gases (GHG) after the bottles were recycled into secondary materials by combining them with virgin materials to reduce costs. The difference in GHG emissions as a result of recycling, incineration and landfill vary between different materials and uses. The benefits of recycling are particularly large, up to 7.64 times, for aluminium because the energy required to recycle the material is much less than that required for primary production of the material; for other materials, notably glass, the differences are generally much smaller. Simon et al. reported that PLA has the lowest GHG of 66 kg CO_2-eq followed by a large 1.5 litre PET bottle at 85 kg CO_2-eq and carton 88 kg CO_2-eq. In this context, PLA seems to be the most environmentally friendly product. However, when PLA bottles had undergone incineration and landfill, GHG emissions had increased several folds to 498 CO_2-eq and 500 CO_2-eq respectively. Increased GHG emissions were also found for other materials such as glass, PET, aluminium and carton disposed of by incineration and landfill. This evidence shows that re-use and recycling should be promoted but end-of-life management should consider energy recovery as an alternative to landfill.

Papong et al. (2014)[3] also compared PLA and PET drinking water bottles. PLA and PET have similar inputs in terms of fuel, electricity, variety of chemicals, water and catalysts. PLA bottles have lower environmental impacts than PET in terms of global warming, reduced dependency on fossil fuel energy and human toxicity. However, it was found that the eutrophication and acidification potential of PLA is higher, due to the use of starch as the input to produce an intermediate monomer of lactic acid for PLA polymerisation. The production process for PLA is complicated in comparison to PET as it requires a variety of additional elements such as fertilisers, herbicides and enzymes as inputs but also has certain advantages as a variety of sources can be used as an energy supply such as the combustion of agricultural residues. The large areas of farming land enable the installation of wind turbines to harness wind energy and reduce dependency on non-renewable fossil fuels. Therefore, there is a wider spectrum for possible routes of pollution through the production of PLA in comparison to PET. The cultivation of cassava roots to produce starch requires fertiliser, herbicides for weeding and diesel for harvesting and transportation from farms, and washout of fertilisers by rainwater can cause run off pollution to lakes and rivers. However, the production of PET drinking bottles relies on petrochemicals such as hydrocarbons, chemicals, catalyst and electricity. Hence leaching to the natural environment is less likely as most of the substances remain within in the boundary of the factory and there is a greater ability to manage and reduce the risks.

Cheroennet et al. (2017)[4] conducted a study to assess and compare the life cycle impact of three types of bio-based boxes: polylactic acid from sugarcane, polylactic acid from sugarcane-starch blends and polybutylene succinate from sugarcane and corn) and petroleum-based boxes of polystyrene. Four locations of the plantation stage were considered in different provinces of Thailand: Kanchanaburi, Sakaeo, Prachinburi, and Chonburi. Carbon footprint and freshwater consumption were assessed in terms of the external environmental cost (unit: THB equivalent). The results indicate that polybutylene succinate has the lowest water footprint, at 0.38 m^3 H_2O, of all the bio-based boxes and presents the second lowest water deprivation at 0.008 m^3 H_2O equivalent. It also has the lowest carbon footprint at −0.06 kg CO_2 equivalent. The polybutylene succinate box showed the lowest total externality cost of 0.046 THB equivalent during the production chain in Sakaeo province. Freshwater consumption accounts for 64–74% of total external cost with carbon footprint accounting for the remaining 26–36%. These results should help the bio-plastics industry to develop with reduced water use and carbon footprint.

The study also indicated that the environmental friendliness of plastic boxes does not solely depend on the selection of materials, but also on factors such as: (1) amount of material used, (2) water source, (3) complexity of production process (4) transportation of the raw material to factory (5) delivery distance to consumer, (6) recyclable and reusability can affect the environmental footprint of plastic products. Transportation is a hugely important factor. For example, the transportation of PLA from the production site at Nebraska, United States to Europe will consume significantly more fuel compared to localised production which can greatly reduce fuel consumption. Transportation routes need to be thoroughly examined to be able to justify the environmental friendliness of plastic products, accounting from the input of raw materials to the production of consumer ready products.

References

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3. If an accurate comparison between the environmental impacts of bio-based and conventional fossil-based plastics cannot be made at present, what barriers exist to making this comparison and what knowledge gaps would need to be addressed to enable us to do so?

A lack of harmonised standards limits the comparison between bio-based and conventional plastics.[1] More information is still needed to confirm the carbon footprints of the biobased plastic products. The environmental friendliness of plastic products are not only dependent on the selection of materials, but also factors such as (1) amount of material used, (2) water source, (3) complexity of production process (4) transportation of the raw material to factory[2] (5) delivery distance to consumer, (6) recyclability and reusability can affect the environmental footprint of the plastic products.

Furthermore, there is the methodological problem that conventional LCA metrics do not account for the environmental persistence of plastics and the damage caused by such durability[3]. To allow for the environmental impacts of plastic waste will require a different methodological approach, yet to be developed.

References

[1] IBioIC, A Review of Standards for Biodegradable Plastics

[2]Lee Tin Sin and Bee Soo Tueen (2019). Polylactic Acid (2nd Edition). A Practical Guide for Processing, Manufacturing and Application of PLA. Elsevier.

[3] Clift et al. (2019), 'Managing Plastics: Uses, Losses and Disposal'. Law, Environment and Development Journal.

4. Bio-based plastics currently make up a relatively small proportion of the market, representing around £50m GVA5. What, if any, are the barriers preventing innovative bio-based products from succeeding in the marketplace?

Principally, current bio-based plastics derived from starch, lactic acid or polyhydroxyalkanoates do not possess the physical properties that are required for wide application. New bio-based polymers based on furan dicarboxylic acids (FDCA) and pyridine dicarboxylic acids (PDCA) offer opportunities, having both widely applicable physical properties and biodegradability as attributes. However, the conventional polymer industry has benefitted from decades of process optimisation and innovation. Functional competitors that are bio-based are typically first-generation technologies and thus incur a cost premium in delivering similar functionality to mainstream applications. Innovation in bio-based polymer technologies needs to be promoted though tax incentives to SMEs investing in circular economies for new and existing polymers derived from renewable feedstocks. Furthermore, the end-of-life costs associated with all polymers should be borne by the manufacturers to level the playing field.

The study of Lettner et al. focussed on identifying the factors influencing the market diffusion of bioplastics by considering the four following biopolymers: polylactic acid (PLA), polyhydroxyalkanoate (PHA), lignin and cashew nut shell liquid (CNSL). Scenario techniques employing effects analysis and cross impact analysis were applied in the assessment. The effects analysis of the study showed that the price of PLA and PHA is influenced by process costs, whereas the prices of CNSL and lignin based novel bio-based plastic materials are influenced by further technological innovations. The sales volume of all four biopolymers largely depended on the price as well as on marketing activities. The cross-impact analysis identifies a range of possible outcomes. While a further price reduction and an increasing sales volume can be assumed likely in the case of PHA and lignin, the scenarios for PLA and CNSL are rather uncertain[1].

References

[1] M. Lettner et al. Journal of Cleaner Production 157 (2017) 289-298

5. The potential impacts of bio-based plastics on waste processing are covered in Chapter 7. What other potential unintended consequences could arise as a result of a growth in use of bio-based plastics?

For all three categories of plastics, people may mistakenly assume that it is more acceptable to discard them thoughtlessly e.g. as litter than is the case for fossil-based plastics. Even where more care is taken in their disposal there may be an assumption that biodegradable materials will 'disappear' in a short period of time, when in fact their degradation rate may be small or in some environments, negligible. Furthermore, the properties of some novel plastics may be inferior to those of fossil-based alternatives, resulting in heavier gauge films and packaging and consequently increased mass of waste.

A slow response of the entire re-use value chain could limit the benefits offered by the greater circularity of bio-based polymers. A failure to upgrade infrastructure to include industrial composters will negate extracting maximum benefit from particularly biodegradable bio-based polymer. Existing spectrophotometric technologies need to be upgraded to allow for the efficient identification and sorting of new bio-based polymers for either dedicated recycling or composting.

Furthermore, bio-based plastics may cause blockages to sewage systems. This is because most bio-based plastics are hydrophilic materials, which tend to absorb water and swell with the size of the material and can increase at least two times compared to their original size. This has the potential to cause the clogging of underground sewage pipes.

Upon disposal to the natural environment and when in contact with water, bio-based plastics especially those blended with cellulosic materials like starch will tend to result in the starch portion of the bio-based plastic being consumed by microorganisms. This will subsequently increase the Biochemical Oxygen Demand (BOD) of lakes and rivers. High BOD in water can endanger the aquatic organisms.

Other unintended consequences of bio-based plastics are similar to those for bio-based transportation fuels. These include, but are not limited to, the displacement of food crops from land to grow plastic feedstocks, high water requirements for bio-based plastic feedstocks particularly in areas of poor irrigation practises or low water availability and the potential for increased leaching of fertiliser into water streams.

In the transportation fuel industry, two ticket systems (Road Transportation Fuel Obligation (RTFO) and Motor Fuels Greenhouse Gas Emissions (GHG)) introduced under the Renewable Energy Directive (RED II) control for unintended consequences such as indirect land use change (ILUC) and penalise high GHG emitting fuels and low bio-volume fuels.

A similar system could be introduced for bio-derived plastics. A ticket system for bio-based and oil-based plastics should account for:

- Any GHG life-cycle savings vs. a baseline
- Water usage during production from oil field/seed to final product
- Land-use requirements (e.g. ILUC)
- See question 6 for end-of-life/recycling points of bio-based plastics which do not have the same final chemical make up as conventional oil-based plastics and as such have low-quality physical properties which limit its contribution in a circular economy.

6. Government has made clear that we want to eliminate all avoidable plastic waste and to move towards a more circular economy. What role, if any, is there for biodegradable plastics to play in achieving the outcomes listed in paragraph 1.7? How could the circularity of these materials be reflected or measured? What is the evidence in support of your view?

Biodegradability relates to how easy it may be to manage the material at end-of-life and to how damaging it may be if released into the unconfined environment. Recycling plastics as part of a circular economy is a high value-adding part of a plastic’s life cycle but biodegradability does not relate to reusability or recyclability, which are the properties determining potential for “circular” use[1]. On the contrary, many biodegradable polymers are less amenable to mechanical or chemical recycling and therefore can be used fewer times than common fossil fuel derived polymers. For instance, the biodegradable polymers polylactic acid (PLA) and polycaprolactone are both produced by condensation polymerisation. During the recycling of these materials, moisture in the biodegradable polymer can lead to depolymerisation which causes the recycled polymer to have weaker mechanical properties. Although recycling is still possible for biodegradable polymers, the know-how to segregate the biodegradable polymers from the conventional polymers remains an issue. Polylactic acid (PLA) can be used to produce beverage bottles; however it is difficult to distinguish these from polyethylene terephthalate (PET) bottles. Moreover, PLA bottles are seldom found in the market so that the effort needed to discriminate and separate PLA from PET is currently not profitable or feasible. It was pointed out in response to Q2 that end of life destruction of plastics is the most GHG intensive phase in the life of a plastic; for example, when PLA bottles undergo incineration and landfill, the GHG emissions can increase several fold to 498 CO_2-eq and 500 CO_2-eq respectively[2]. The more times a plastic can be recycled, the more diluted the CO_2e production from the end of life process becomes per use.

The difficulty of separating bio-degradable plastics into a suitable low-quality stream in the waste process can reduce the quality of the whole plastic waste stream due to the mixing of low-quality bio-degradable plastic with high quality conventional plastic. If this mixing reduces the re-usability of the whole plastics waste stream this will increase overall GHG emissions by offsetting any early life stage CO_2e savings of bio-based plastics and compromise the whole premise of a sustainable circular economy.

In some convenience uses, conventional plastics may be replaced by biodegradable materials, such as paper and other vegetable fibres as well as biodegradable plastics. However, the scope for replacement of conventional plastics is limited[2]. Additionally, trade-offs when substituting plastics with materials such as cotton, e.g. for bags which increases the consumption of non-renewable resources and land use for agricultural production must be taken into consideration; see Q1. Any benefits from the use of biodegradable plastics arise at end-of-life but must be considered carefully by assessing the whole life cycle including management at end-of-life. Many conventional plastics are stable in landfill sites so that their carbon content is sequestered. By contrast, bio-degradable plastics in landfills may react to form methane, which has a higher GHG effect than carbon dioxide. If waste plastic is managed by energy recovery, biodegradability is irrelevant. Food waste or composite materials may be composted after single use along with structurally compromised polymer in industrial composters and returned to the environment as biomass-enriched soil. Alternatively, biodegradable plastics can be treated along with food or agricultural waste by anaerobic digestion as an efficient rote to energy recovery[3]. The multiplicity of uses and management systems for plastics underlines the conclusion that any advantages of using biodegradable plastics must be assessed in the context of the whole life of the material.

In summary, bio-degradable plastics usually:

a) Cannot be recycled at all due to such low-quality physical properties
b) Cannot be recycled enough times to neutralise the CO_2e from disposal after less use due to low quality physical properties
c) Cause a reduction in the quality of the whole plastics recycling stream, lowering the total re-use potential of all plastics due to the un-availability of waste-stream separation techniques

For these reasons, it may be difficult for bio-degradable plastics to be a sustainable part of a circular economy.

To measure and control the circularity of a bio-degradable plastics, the number of re-use cycles a bio-degradable plastic can achieve based on its physical qualities could be accounted for in a ticket system. See Q5 for reference to the RED II ticket system. A ticket system which accounts for the increase in GHG emission from a reduced life-duration of a bio-degradable plastic (or non-conventional bio-based plastic) and the increase in GHG effect from the release of methane upon decomposition should be applied to the manufacturing of bio-degradable and non-biodegradable plastics to try and drive the manufacturing of sustainable plastic on reduced cost penalties. The idea that a consumer could pay a deposit for a plastic item (particularly bags and bottles) which they get back if the items are returned to a designated recycling center could encourage the circular economy.

The benefits of biodegradability arise for materials that leak from the economy into the unconfined environment[1,4]. Therefore standards for biodegradability must refer to unconfined environments, particularly marine environments, and not be restricted to controlled environments such as exist in composting or digestion.

References

[1] Clift et al. (2019), 'Managing Plastics: Uses, Losses and Disposal'. Law, Environment and Development Journal.

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[4] IBioIC, A Review of Standards for Biodegradable Plastics

7. With existing technology and materials, what would be the minimum timeframe for complete biodegradation (breaking down to nothing but water, biomass, and gasses, such as carbon dioxide or methane) for plastics designed to biodegrade? We would particularly welcome an assessment in the following environments:

- **Deep Sea**
- **Surface of the Sea**
- **Freshwater**
- **Beach**
- **Soil – surface**
- **Soil – lightly buried**
- **Landfill**
- **Industrial composting**
- **Home composting**

IBioIC produced a comprehensive report on the biodegradability of bioplastics in a number of environments.[1] The report collates degradation rates for a number of bio-based polymers in a variety of environments, demonstrating that biodegradation is highly variable depending on the conditions. Nevertheless, degradation rates remain in the order of months rather than decades as may be the case for durable polymers.

The requirement for the bio-degradation timescale should also take into account that the plastic will escape the circular economy and make its way into the ocean. Once in the ocean, the maximum timeframe for biodegradation should be defined by the rate at which it passes through the micro and nano plastic phases which needs to be shorter than a fraction of the lifespan of the shortest living creature that could consume it. This is to prevent accumulation and the harmful effects of micro and nano plastics on aquatic and marine life which are described in references [2,3,4,5,6].

Additionally, please refer to Q8, Q9 and Q10.

References

[1] IBioIC, A Review of Standards for Biodegradable Plastics

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[5] Microplastics on beaches: ingestion and behavioural consequences for beachhoppers, Marine Biology, Louise Tosetto et al, 2016

[6] Microplastics in the environment: A critical review of current understanding and identification of future research needs, Zeynep Akdogan, Environmental Pollution Vol 254, Nov 2019

8. What evidence is available of direct impacts of biodegradable waste plastics on biodiversity, ecosystems, and the natural environment in the short-term (over the degradation period of the item), and in the long term (including cumulative effects)?

We know that plastic degradation occurs by going through the process of bio-fragmentation[1], which is the breakdown into micro-plastics, and as such further into nano plastics. There are many articles on the harm of micro and nano plastics, particularly on water-based eco-systems[2,3,4,5,6] for their development and survival rates. These negative effects on the organisms include the effect of the increased concentration of harmful contaminants that adsorb and live on the micro-plastics. If bio-degrading plastics result in a greater mass percent of micro plastics in the oceans, then the impacts both on short and long term can be very negative for these ecosystems and potentially humans and must be urgently addressed.

An early study on the types of microorganisms involved in biodegradation was carried out by Torres et al. (1996)[7] using various microorganism strains. The aim was to screen for the microorganisms involved in the biodegradation of PLA and lactic-acid-containing polymers. Initially, the researchers used DL-lactic acid (DL-LA) and its oligomers to investigate the extent of filamentous fungi reactivity in 7 days. Torres et al. (1996) conducted two analyses on DL-LA and oligomers separately at a concentration of 10 g/liter, and sterilization was undertaken to avoid biological contamination, which can produce faulty results. The results showed that all strains could actively consume lactic acid and oligomers. Out of the analysed strains, only three strains could totally utilise DL-LA and DL-LA oligomers as the sole carbon and energy source (two strains of *Fusarium moniliforme* and one strain of *Penicillium roqueforti*). Other strains could only partially assimilate the DL-lactic acid and oligomer substances. This indicates that lactic acids merely serve as sources of assimilation for selected strains. The biomass production of the strains remained higher for *Fusarium moniliforme* and *Penicillium roqueforti*. Yield of biomass from strain assimilation is always favorable as a source of plant nutrients.

An investigation on the different types of fungal strains growing on poly(lactide-co-glycolide) found that only *Fusarium moniliforme* (Fmm) grew on the specimens after a 2-month period. Figure 3 in Appendix B shows the formation of mycelia on the surface of a specimen. Enlargement of the image (see arrow) shows that the *Fusarium moniliforme* filaments had penetrated the specimen to some depth. This is thought to be related to the way in which microorganisms attack the cutin of plants to cause infection (Torres et al., 1996). Cutin is the structural component of the plant cuticle. It is a polyester composed of ω-hydroxy-C_{16} and C_{18} fatty acids, dihydroxy-C_{16} acid, 18-hydroxy-9,10-epoxy-C_{18} acid and 9,10,18-trihydroxy-C_{18} acid. This insoluble polymer constitutes a major physical barrier that helps to protect plants from penetration by pathogenic fungi. Pathogenic fungi produce an extracellular cutinase when grown on cutin as the sole source of carbon (Kolattukudy et al., 1987). Since PLAGA copolymer is also a type of polyester, the degradation mechanism is similar. The degradation starts with abiotic degradation, which causes the transformation of PLA into its oligomers and the attachment of strain filaments onto the PLGA. This leads to the conclusion that PLAGA is a bio- assimilable polymer. A very similar observation was made when PLA was buried in natural soil for a 2-month period. Filamentous fungi also grew on and penetrated the polymer mass, as shown in Figure 4 in Appendix B.

Rudeekit et al. (2008)[8] conducted a biodegradation test of PLA under wastewater treatment, landfill, composting plant and controlled composting conditions. The researchers found that the PLA sheets had noticeable white spots on the surface after a 1-month exposure to wastewater treatment conditions and the areas affected by the white spots had grown significantly larger over the testing period. However, the biodegradation of PLA was more rapid under composting plant conditions at high temperature and humidity (50–60°C and relative humidity (RH) >60%). The PLA sample in sheet form became brittle and started to break into small pieces after testing for 8 days.

This is because the degradation temperature at a land composting plant is higher than the glass transition temperature of PLA. Thus, when the temperature exceeds the glass transition temperature this causes chain movement, enabling the penetration of water to progress the hydrolysis reaction. The importance of this mechanism is illustrated by comparing the rate of biodegradation of the land composting plant and wastewater treatment conditions. This shows that despite the large volume of water in contact with PLA in the wastewater treatment conditions, due to the degradation temperature being lower than the glass transition temperature, the degradation rate is significantly lower than that under composting plant conditions.

When the PLA sheets were buried in the landfill conditions, they degraded more slowly than those in the composting plant conditions. Again, this is because of the higher temperature and humidity in the composting plant conditions, which help the PLA to degrade rapidly. In the landfill conditions it required 6 months for major fragmentation to occur and 15 months for there to be some disappearance. In contrast, PLA under composting plant conditions showed disappearance in merely 30 days. It is possible to conclude that the degradability of PLA is dependent on the hydrolysis and cleavage of ester linkages in the polymer backbone to form oligomers. Please refer to the journal paper to view detailed images of the degradation of PLA samples under wastewater treatment, landfill and composting conditions.

More research is necessary to evidence these direct impacts of biodegradable waste plastics on biodiversity, ecosystems, and the natural environment in the short-term and in the long term. noting that the impact would likely be less significant when compared to more durable polymers, i.e. the persistence of biodegradable polymers will likely be lower than for durable polymer even when considering lower biodegradation rates under sub-optimal conditions.

References

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[6] Microplastics in the environment: A critical review of current understanding and identification of future research needs, Zeynep Akdogan, Environmental Pollution Vol 254, Nov 2019

[7] Torres, A., Li, S.M., Roussos, S., Vert, V., 1996. Screening of microorganisms for biodegradation of poly (lactic acid) and lactic acid-containing polymers. Appl. Environ. Microbiol. 62, 2393–2397.

[8] Metabolism of Plant Lipids, ACS Symposium Series, vol. 325, pp. 152–175.
Rudeekit, Y., Numnoi, J., Tajan, M., Chaiwutthinan, P., Leejarkpai, T., 2008. Determining biodegradability of polylactic acid under different environments. J. Met., Mater. Miner. 18, 83–87.

9. To what extent, if at all, can the existing evidence be used to extrapolate the degradation rate of plastics in different environments (e.g. in surface water vs deep sea, etc.)?

No effective models exist to predict degradation rates in novel environments based on the degradation rates under well-studied conditions. Primarily there is insufficient data to confidently build such models and any extrapolation based on the sparsely available degradation rate data[1] would be subject to a high degree of uncertainty.

Understanding the environmental degradation of PLA is very important because more than 100,000 MT of PLA is produced annually – mainly for consumer products and packaging. Therefore, most of this PLA will be disposed in landfill sites after a short period of use. PLA undergoes biodegradation via aerobic and anaerobic pathways and depends on the presence of oxygen for assimilation by bacteria and fungi.

Some of the methods that have been used to measure the biodegradation of biopolymers in the environment include measuring the consumption of oxygen, weight losses, biogas generation and carbon dioxide production. Several material properties can influence the biodegradation of PLA, including the molecular weight, stereo complex and crystallinity. At the same time, external aspects, such as moisture, sunlight, temperature, presence of a solvent and oxygen supply, can also significantly affect its rate of biodegradation. Massardier-Nageotte et al. (2006)[2] conducted a study on the aerobic and anaerobic biodegradation of commercially available plastics. Please refer to the reference to see detailed results of the study.

Typical data indicates that PLA is durable and can resist degradation for a longer time compared to other biopolymers, while still maintaining its biodegradable characteristics. It is very important for PLA to maintain its functionality for a range of applications that involve long-term use, such as woven fabrics and matting. These products can be used until worn out and then disposed of for biodegradation, when the material finally transforms to a harmless residue in the natural environment.

This leads to the question, ‘how long does it take for PLA products to fully degrade?’ Kale et al. (2007)[3] conducted a biodegradability study on polylactide bottles in real and simulated composting conditions. The PLA 500 ml bottles used to package spring water were subjected to real composting burial and international standard of ASTM D5338 and ISO 14855-1 under controlled conditions.

When PLA bottles were buried in a compost pile made of cow manure, wood shavings and waste feed (i.e. the feed that the cows left) for 30 days, the bottles had totally decomposed by the end of the test period. Kale et al. (2007) reported that the higher temperature produced in the compost pile (65°C), as a result of microbiological action and environmental heat caused a distortion of the PLA bottles in days 1 and 2. This temperature is higher than the glass transition temperature (T_g) of PLA (60.6°C). The structure of the bottles remained tough until days 6 to 9, when a powdery texture appeared on the surface and fragmentation occurred. The bottles lost their structure and by day 15 a large portion of the bottle had composted. No visible residue was found by day 30. The chronology of PLA bottle biodegradation in the compost pile is illustrated in Figure 5 in Appendix B.

References

[1] IBioIC, A Review of Standards for Biodegradable Plastics

[2] Kale, G., Auras, R., Singh, S.P., Narayan, R., 2007. Biodegradability of polylctide bottles in real and simulated composting conditions. Polym. Test. 26, 1049–1061.

[3] Massardier-Nageotte, V., Pestre, C., Cruard-Pradet, T., Bayard, R., 2006. Aerobic and anaerobic biodegradability of polymer films and physico-chemical characterization. Polym. Degrad. Stabil. 91, 620–627.

10. What testing regimes/methodologies are you aware of that could verify that biodegradable plastics completely degrade (breaking down to just water, biomass, and gasses, such as carbon dioxide or methane) in the open environment instead of simply fragmenting into microplastics? If not, what are the key challenges to establishing such a test?

We are uncomfortable with any implicit assumption that degradation is invariably preferable to physical breakdown alone. Under anaerobic conditions methane, a highly potent greenhouse gas, is produced, potentially a greater problem than the burial or disposal of plastic fragments.

EN 17033:2018 and ISO/DIS 22403 offer standardised testing regimes for terrestrial and marine degradation using cellulose as a control.

Investigation of PLA biodegradation using the cumulative measurement respirometric (CMR) system (according to ASTM D5338 and ISO 14855-1) showed that the biodegradation of PLA bottles required >30 days burial in a compost pile to achieve 80% mineralisation. CMR is a system designed to yield the percentage of carbon dioxide from the organic carbon content of a sample.

Standards developed by ASTM and ISO evaluate the biodegradation of biodegradable plastic materials in simulated controlled composting conditions. Kale et al. (2007)[1] investigated the biodegradation performance of polylactide (PLA) bottles under simulated composting conditions according to ASTM D5338 and ISO 14855-1 standards and compared these results with a novel method of evaluating package biodegradation in real composting conditions. Two simulated composting methods were used in this study to assess biodegradability of PLA bottles: (a) a cumulative measurement respirometric (CMR) system and (b) a gravimetric measurement respirometric (GMR) system. Please refer to the study to find further details on the methodology used.

Kale et al. (2007) reported that the rate of biodegradation of PLA, and biopolymers in general, differs for real in-soil burial and simulated composting, as revealed by CMR. Simulated composting has a higher rate of biodegradation, mainly due to the smaller sample sizes used in testing, which enhances the hydrolysis and provides a larger surface for the reaction of microorganisms. In real composting conditions, the rate of biodegradation tends to be slower due to the humidity, the compost raw materials, the types of microorganisms and the larger size of the disposed products. Consequently, Kale et al.

(2007) concluded that it is essential to conduct real composting tests to ensure that biopolymer products can successfully biodegrade and decompose in commercial composting facilities and landfills.

References

[1] Kale, G., Auras, R., Singh, S.P., Narayan, R., 2007. Biodegradability of polylctide bottles in real and simulated composting conditions. Polym. Test. 26, 1049–1061.

11. Would such testing regimes/methodologies be applicable to plastics which contain prodegradant agents intended to aid the biodegradation process? We are particularly interested in any evidence established in the last three years.

The Ellen MacArthur Foundation concluded that “since oxo-degradables and similar additives designed to encourage degradation hinder the circular economy for plastics and do not bring any benefit to leakage, and so should be banned.”[1]

Certain species of microorganisms can be added to improve the biodegradable process. Please refer to answers for Q.8 and Q10.

References

[1] Ellen MacArthur Foundation, McKinsey & Company (2016) World Economic Forum: The New Plastics Economy—Rethinking the Future of Plastics

12. What evidence, if any, is available to quantify the differing environmental impacts of compostable plastics when they “escape” and then degrade in the open environment?

Controlled field trials are limited in characterising environmental impacts. Spierling et al. (2018)[1] provides a review of life cycle assessments (LCA) associated with bio-based plastics, concluding that only global warming potential represented a comparative metric owed to a lack of harmonised standards.

References

[1]Spierling et al. (2018), *Bio-based plastics – A review of environmental, social and economic impact assessment*, Journal of Cleaner Production, 185, 476-491.

13. The potential impacts of biodegradable plastics on waste processing are covered in Chapter 7. What other potential unintended consequences could arise as a result of a growth in use of biodegradable plastics?

Please refer to Q2 and Q5.

14. What evidence, if any, is available regarding the suitability of the existing industrial and home composting standards? We welcome any suggestions on how these standards could be adapted to current and future needs, if necessary.

No comment

15. To what extent, if at all, would a home composting standard that covers all home composting techniques, equipment and environments in the UK be possible? If so, would it be a desirable system to adopt?

Home composting environments are highly variable and will differ widely in composition, microbial population, density, temperature, humidity and physical state. Consequently, an overall standard would be extremely difficult to establish.

16. The potential impacts of compostable plastics on waste processing are covered in Chapter 7. What potential unintended consequences could arise as a result of a growth in use of compostable plastics?

No comment

17. A list of currently active biodegradability standards and test methods for all plastic materials in soil, marine and wastewater environments is included in the report 'A Review of Standards for Biodegradable Plastics'. Are there other relevant standards or test methods for those circumstances that you are aware of that do not appear on this list?

ASTM plastic biodegradation standards

ASTM Standard	Description
D6400-12	Standard Specification for Labelling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities
D6954-18	Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation
D6868-17	Standard Specification for Labelling of End Items that Incorporate Plastics and Polymers as Coatings or Additives with Paper and Other Substrates Designed to be Aerobically Composted in Municipal or Industrial Facilities
D5338-15	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures
D7473-12	Standard Test Method for Weight Attrition of Plastic Materials in the Marine Environment by Open System Aquarium Incubations
D6691-17	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum
D5929-18	Standard Test Method for Determining Biodegradability of Materials Exposed to Source-Separated Organic Municipal Solid Waste Mesophilic Composting Conditions by Respirometry
D5526-18	Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under Accelerated Landfill Conditions

D7475-11	Standard Test Method for Determining the Aerobic Degradation and Anaerobic Biodegradation of Plastic Materials under Accelerated Bioreactor Landfill Conditions
D5988-18	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil
D5511-18	Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions

ISO plastic biodegradation standards

ISO 15985:2014	Plastics — Determination of the ultimate anaerobic biodegradation under high-solids anaerobic-digestion conditions — Method by analysis of released biogas
ISO 14853:2016	Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system — Method by measurement of biogas production
ISO 10210:2012	Plastics — Methods for the preparation of samples for biodegradation testing of plastic materials
ISO/DIS 13975	Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in controlled slurry digestion systems — Method by measurement of biogas production
ISO 19679:2016	Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sediment interface — Method by analysis of evolved carbon dioxide
ISO 13975:2012	Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in controlled slurry digestion systems — Method by measurement of biogas production
ISO 18830:2016	Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sandy sediment interface — Method by measuring the oxygen demand in closed respirometer
ISO/DIS 22404 (under development)	Plastics — Determination of the aerobic biodegradation of non-floating materials exposed to marine sediment — Method by analysis of evolved carbon dioxide

ISO 17556:2012	Plastics — Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
ISO/DIS 17556 (under development)	Plastics — Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
ISO 14855-1:2012	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions — Method by analysis of evolved carbon dioxide — Part 1: General method
ISO 17088:2012	Specifications for compostable plastics
ISO 16929:2013	Plastics — Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test
ISO/DIS 16929 (under development)	Plastics — Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test
ISO 15270:2008	Plastics — Guidelines for the recovery and recycling of plastics waste
ISO 846:1997	Plastics — Evaluation of the action of microorganisms
ISO 20200:2015	Plastics — Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test

BS, CEN, DIN plastic biodegradation standard

BS 8472	Methods for the assessment of the oxo-biodegradation of plastics and of the phyto-toxicity of the residues in controlled laboratory conditions
BS ISO 13975	Plastics. Determination of the ultimate anaerobic biodegradation of plastic materials in controlled slurry digestion systems. Method by measurement of biogas production
DIN EN ISO 10210	Plastics - Methods for the preparation of samples for biodegradation testing of plastic materials (ISO 10210:2012); German version EN ISO 10210:2017

DIN EN ISO 19679	Plastics - Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sediment interface - Method by analysis of evolved carbon dioxide (ISO 19679:2016); German version EN ISO 19679:2017
DIN EN ISO 14853	Plastics - Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system - Method by measurement of biogas production (ISO 14853:2016); German version EN ISO 14853:2017
DIN EN ISO 18830	Plastics - Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sandy sediment interface - Method by measuring the oxygen demand in closed respirometer (ISO 18830:2016); German version EN ISO 18830:2017
DIN EN ISO 15985	Plastics - Determination of the ultimate anaerobic biodegradation under high-solids anaerobic-digestion conditions - Method by analysis of released biogas (ISO 15985:2014); German version EN ISO 15985:2017
DIN EN 13432	Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging; German version EN 13432:2000
DIN 38412-26	German standard methods for the examination of water, waste water and sludge; bio-assays (group L); surfactant biodegradation and elimination test for simulation of municipal waste water treatment plants (L 26)
DIN EN ISO 17556	Plastics - Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved (ISO 17556:2012); German version EN ISO 17556:2012 Edition 2012-12
DIN EN ISO 14855-2	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide - Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test (ISO 14855-2:2018); German version EN ISO 14855-2:2018
DIN EN ISO 20200	Plastics - Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test (ISO 20200:2015); German version EN ISO 20200:2015
DIN EN ISO 14851	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by measuring the oxygen demand in a

	closed respirometer (ISO 14851:1999); German version EN ISO 14851:2004
DIN EN ISO 14852	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide (ISO 14852:2018); German version EN ISO 14852:2018
DIN EN ISO 16929	Plastics - Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test (ISO/DIS 16929:2018); German and English version prEN ISO 16929:2018
DIN EN 14995	Plastics - Evaluation of compostability - Test scheme and specifications; German version EN 14995:2006
DIN EN 17033	Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods; German version EN 17033:2018
DIN EN 16935	Bio-based products - Requirements for Business-to-Consumer communication and claims; German version EN 16935:2017
DIN EN 14987	Plastics - Evaluation of disposability in waste water treatment plants - Test scheme for final acceptance and specifications; German version EN 14987:2006
DIN EN 16848	Bio-based products - Requirements for Business to Business communication of characteristics using a Data Sheet; German Version EN 16848:2016
DIN EN 15347	Plastics - Recycled Plastics - Characterisation of plastics wastes; German version EN 15347:2007
DIN EN 16640	Bio-based products - Bio-based carbon content - Determination of the bio-based carbon content using the radiocarbon method
DIN EN ISO 846	Plastics - Evaluation of the action of microorganisms (ISO/DIS 846:2018)

18. What areas, if any, would require improvement in existing standards to strengthen their effectiveness? To what extent, if at all, would the development of new standards for biodegradability constitute a viable alternative? What is the evidence in support of your view?

It is essential that standards relating to biodegradation and bioplastics or any potential substitute material, takes into account the full life cycle of the relevant material or product, from embedded carbon in manufacture to eventual disposal.

19. When dealing with biodegradation, what are the advantages and disadvantages of producing standards? We would welcome your thoughts in relation to the production of standards at the following levels:

- **National**
- **Regional**
- **International**

No comment

20. Are you aware of any past or current work on a national, regional or international level to implement biodegradability standards?

No comment

21. To what extent, if at all, could biodegradability standards be beneficial for specific products (such as carrier bags) or product forms (for example those that with current technology are typically too contaminated to be mechanically recycled once disposed of)?

The only option for materials which are too contaminated to be mechanically recycled is to be disposed of via landfill or incinerated. It will be of little value to design certain products for biodegradation as the residues can contain further hazardous substances and present hygiene issues when in contact with living organisms.

22. What standards, labelling, and/or certification schemes are currently in place to determine the level of bio-based content in bio-based plastics?

No comment

23. To what extent, if at all, should current labelling requirements be changed to produce new suitable standards?

No comment

24. To what extent, if at all, should specific labelling rules apply to bio-based plastics to certify their proportion of bio content – either to better inform consumers or for any other reason?

No comment

25. What evidence, if any, is available on the impacts that biodegradability certification and labelling systems may have on consumers' behaviour towards the disposal of items carrying such labels?

No comment

26. What, if any, evidence is available to demonstrate the impact that biodegradable (including compostable) plastics have in the current waste management system, including on the quality and safety of composts and digestates? Does the existing evidence allow to estimate the monetary value of this impact?

No comment

27. What, if any, evidence is available on the behaviour of bio-based plastics compared to conventional fossil-based plastics in the current waste management system?

As 7.2(b) briefly suggests, the processability in the recycling process, and the processability, properties and hence economic value of the resulting recyclate, depend critically on the composition of the plastic 'waste'. The variability of the waste feedstock will be difficult to deal with and the presence of certain specific materials will have a serious deleterious effect. Special attention should be paid to chlorinated plastics (whether fossil or bio-based) such as PVC. There are excellent examples of improving environmental impact and recyclability such as the replacement of poly (vinylidene chloride) coated polypropylene barrier films for snack food packaging by metallised polypropylene (which can be recycled, albeit with greater difficulty than uncoated film).

A key step forward would be the design and use of packaging and other products to use only one polymer type (e.g. bottle, cap and label all from similar compatible polymers of the same family).

Please refer see Q5 for more details on concerns relating to the behaviour of bio-plastics in the current waste management system.

28. How, if at all, would waste collection systems need to be adapted to accommodate the niche introduction of biodegradable plastics?

Labelling and education are the most important. A standard label (more effective in words) needs to be introduced and advertised so that consumers know how to differentiate biodegradable plastics from conventional plastics.

29. How, if at all, would waste collection systems need to be adapted to accommodate the mass introduction of biodegradable plastics?

No comment.

30. How do anaerobic digestion, composting, and energy-from-waste operators currently manage compostable plastics in areas where food waste is collected in bags/liners?

No comment.

31. Is there any other information or evidence related to this topic that government should be aware of?

No comment

Appendix A

Working Group

IChemE would like to thank the Working Group which consisted of members from the Sustainability, Education and Biochemical Engineering Special Interest Groups for sharing their expertise for this consultation. They include:

Professor Roland Clift – Professor Emeritus at the Centre for Environmental Strategy, University of Surrey, UK.

Dr. David Brown – Honorary Professor Aston University, Aston University, UK. Director, Trihelica Ltd.

Professor Alex Conradie – University of Nottingham, UK, Green Chemicals Beacon of Excellence.

Dr Tin Sin Lee – Associate Professor in Chemical Engineering, Universiti Tunku Abdul Rahman, Malaysia

Dr Marta Granollers-Mesa – Lecturer in Chemical Engineering, Aston University, UK.

Miss Alice Robinson, CEng – Strategic Planning Analyst, Refining.

Dr James Winterburn – Senior Lecturer in Chemical Engineering, University of Manchester, UK.

Appendix B

Q2.

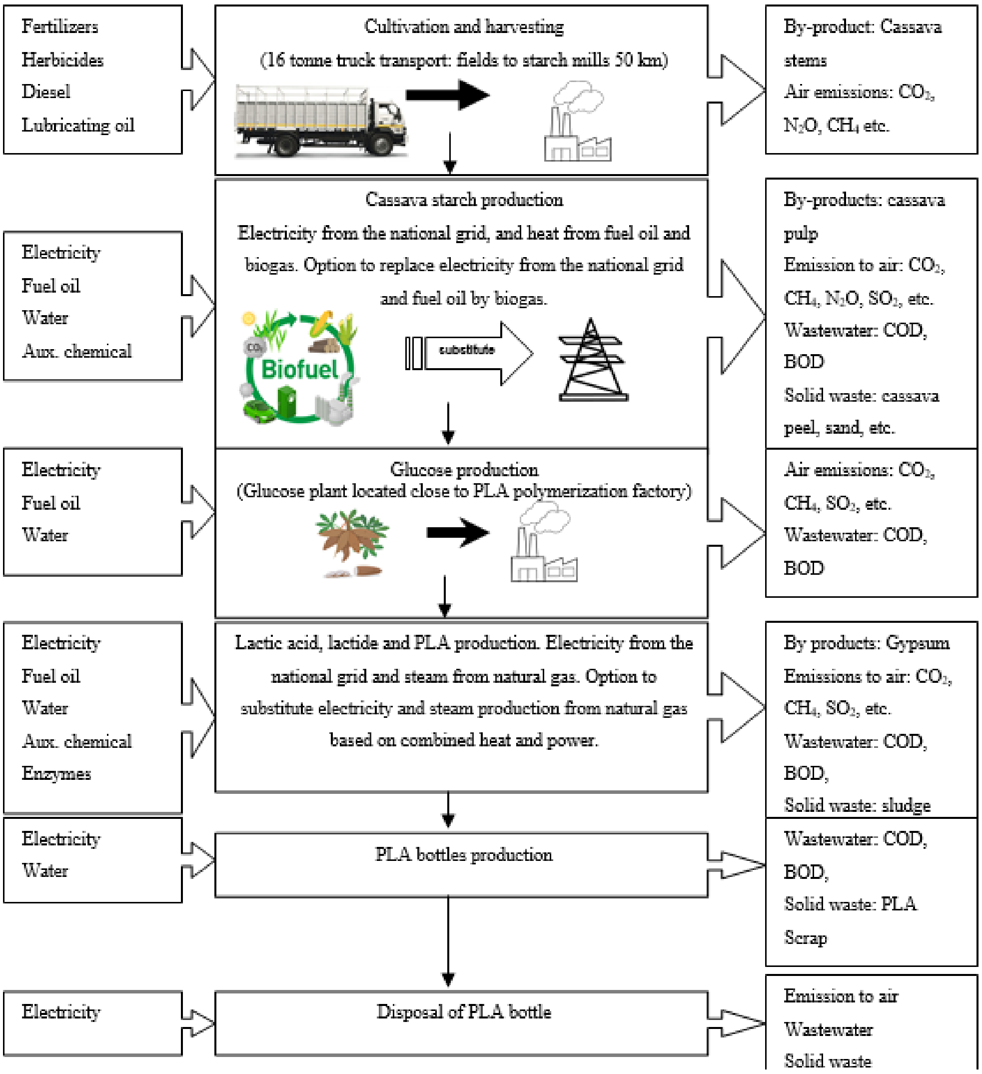

Figure 1. PLA bottles production – inputs, process and emissions (Papong et al.2014)

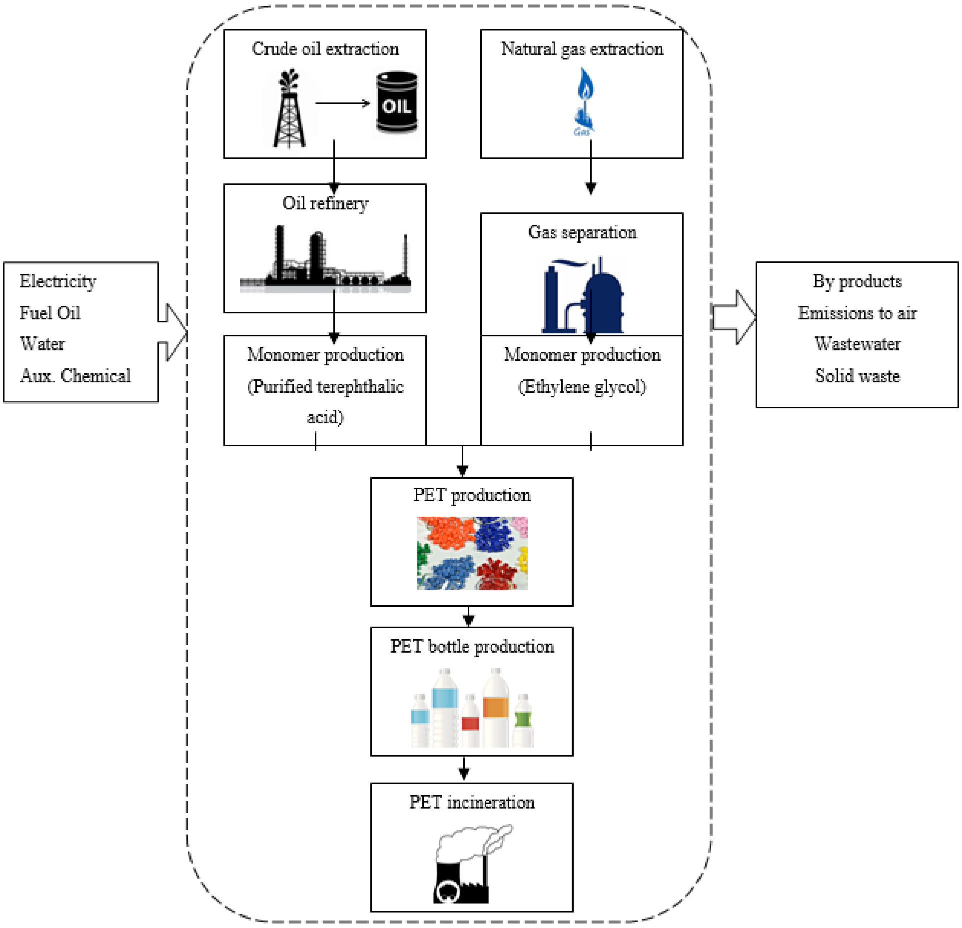

Figure 2. PET bottles production – inputs, process and emissions (Papong et al. 2014)

Q8.

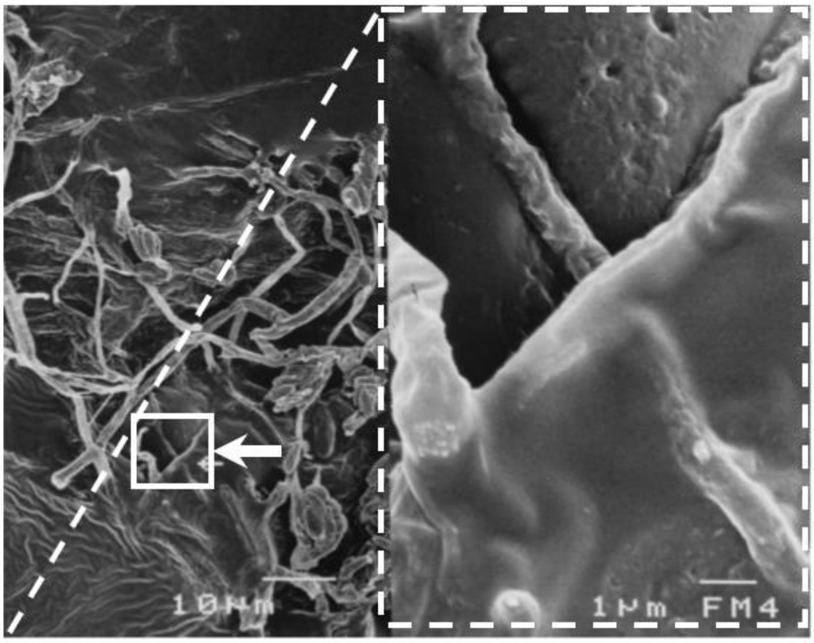

Figure 3. Scanning electron micrographs indicating the penetration of *Fusarium moniliforme* filament in depth of PLAGA copolymer after incubation for 2 months which the enlargement is shown in the left side (adapted from Torres et al., 1996)

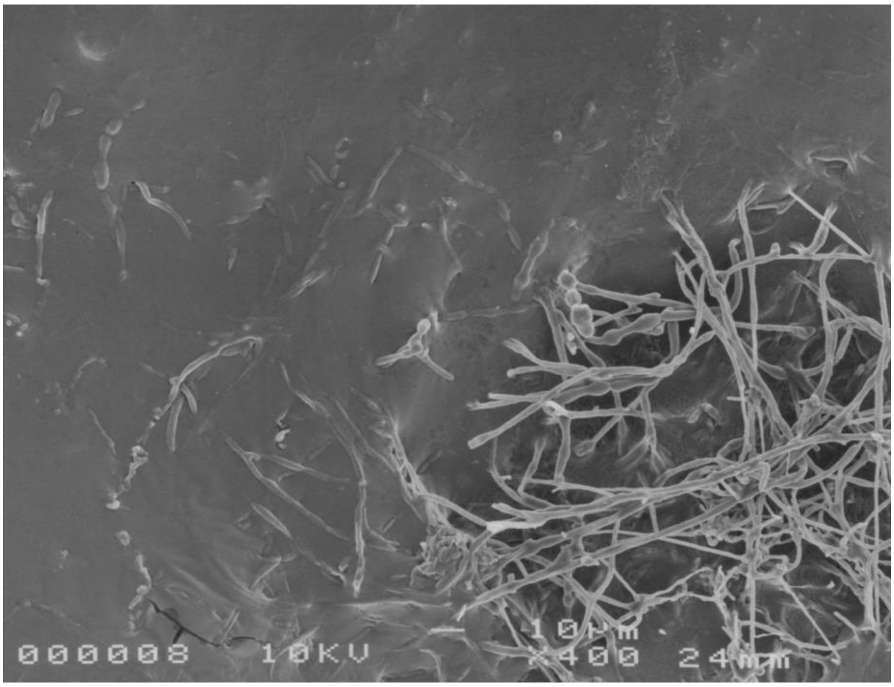

Figure 4. Scanning electron micrograph indicating the growth of filamentous fungi at the surface of a racemic PLA plate buried for 8 weeks in a local natural soil and allowed to age for 8 more weeks at 30 ºC in a hydrated environment (adapted from Torres et al., 1996)

Q9.

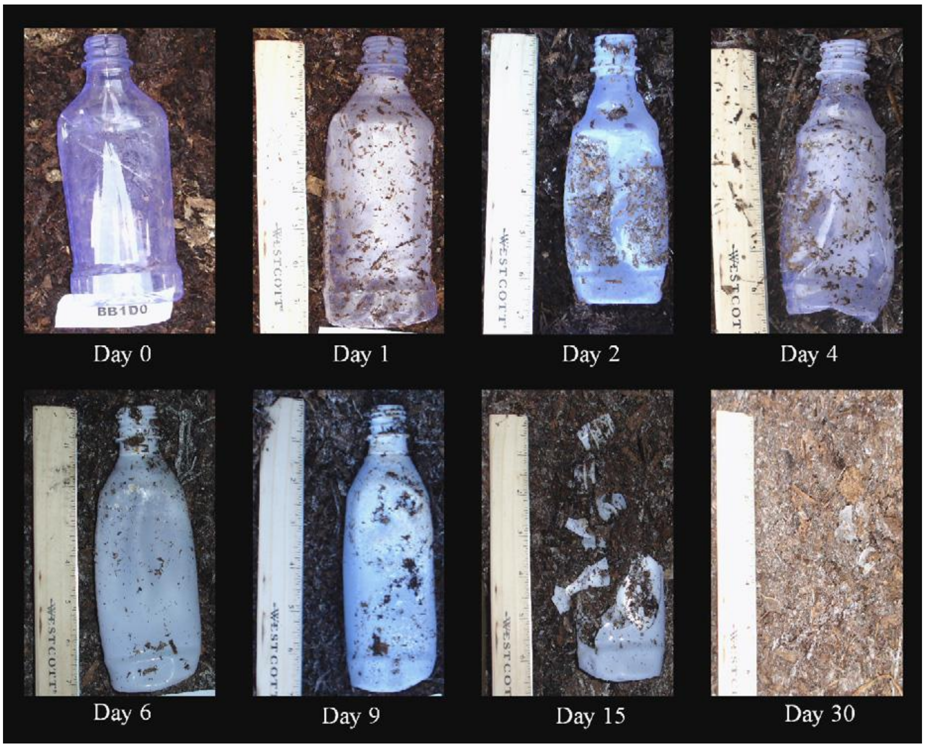

Figure 5. Biodegradation of PLA bottle in compost pile (adapted from Kale et al., 2007)

What is chemical engineering?

Chemical, biochemical and process engineering is the application of science, maths and economics in the process of turning raw materials into every day, and more specialist, products. Professional chemical engineers design, construct and manage process operations all over the world. Oil and gas, pharmaceuticals, food and drink, synthetic fibres and clean drinking water are just some of the products where chemical engineering plays a central role.

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